REMARKS

Claims 59-88 are pending and have been rejected. Claims 59, 67, and 77 have been amended. Reconsideration and allowance of Claims 59-88 in view of the above amendments and following remarks is respectfully requested.

Amendment of the Independent Claims

The pending independent claims, Claims 59, 67, and 77, have been amended by deleting the phrase "the plurality of cups having a pitch less than a millimeter." The amendments to Claims 59, 67, and 77 restore the claims to their originally presented form. Entry of the amendment is respectfully requested.

The Rejection of Claims 59-66 and 77-88 Under 35 U.S.C. § 103(a)

Claims 59-66 and 77-88 stand rejected under 35 U.S.C. § 103(a) as being unpatentable over U.S. Patent No. 4,608,493, issued to Hayafuji in view of U.S. Patent No. 4,724,324 issued to Liebert. Withdrawal of the rejection is respectfully requested for the following reasons.

Independent Claim 59 recites an array that includes a plurality of Faraday cups and "a partially insulated conductive housing in which the plurality of cups is supported, the conductive housing being electrically connected to a reference potential." Claims 60-66 depend from Claim 59. Independent Claim 77 recites an array of Faraday cups and "a partially insulated conductive housing in which the plurality of cups is supported, the conductive housing being electrically connected to a reference potential." Claims 78-88 depend from Claim 77. The claimed array includes a plurality of Faraday cups in which each cup is electrically and capacitively decoupled from all others, a feature that the cited references fail to teach or suggest.

The Hayafuji reference describes a Faraday cup supported in a cavity etched into a semiconductor-type wafer substrate. The reference teaches that the substrate is an insulative substrate. At Col. 4, line 55, the insulative substrate is described as a "substrate 11 of electrically

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isolating material." At Col. 7, line 57-58, the insulative substrate is further described as "a wafer of silicon single crystals." Attached for the Examiner's consideration is Exhibit A, a copy of a portion of "Microelectronic Circuit Design," Richard C. Jager, WCB/McGraw-Hill, 1997, pages 25-30, relating to solid-state electronic materials. At page 30, section 2.5, equation (2.9), the text states that the resistivity of single crystal silicon is 3.38E5 Ohm*cm. Materials with resistivities greater than 1E5 Ohm*cm are insulators. See page 25, section 2.1, paragraph 1 of Exhibit A. The Liebert reference is silent with regard to a supporting substrate.

Thus, in contrast to the claimed invention in which the array includes Faraday cups that are electrically and capacitively decoupled from each other by use of "a partially insulated conductive housing in which the plurality of cups is supported, the conductive housing being electrically connected to a reference potential," the cited references fail to teach or suggest such a feature.

Because the cited references, either alone or in combination, fail to teach, suggest, provide any motivation to make, or otherwise render obvious the invention as claimed, the claimed invention is nonobvious and patentable over the cited references. Withdrawal of this ground for rejection is respectfully requested.

The Rejection of Claims 67-76 Under 35 U.S.C. § 103(a)

Claims 67-76 stand rejected under 35 U.S.C. § 103(a) as being unpatentable over the Hayafuji reference in view of U.S. Patent No. 4,992,742, issued to Okuda. Withdrawal of the rejection is respectfully requested for the following reasons.

Independent Claim 67 recites an array of Faraday cups and "a partially insulated conductive housing in which the plurality of cups is supported, the conductive housing being electrically connected to a reference potential." Claims 68-76 depend from Claim 67. The

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claimed array includes a plurality of Faraday cups in which each cup is electrically and capacitively decoupled from all others, a feature that the cited references fail to teach or suggest.

Like the Hayafuji reference, the Okuda reference describes a Faraday cup array in which the cups are supported in an insulating substrate. At Col. 1, lines 62-65, the reference states that "insulating plate 4 defines the positional arrangement of the plurality of collector electrodes 3." At Col. 6, line 60 (Claim 3), the insulative substrate is further described as "an electrically insulating member on which said particle trapping member and said recoil particle trapping member are mounted."

The Okuda reference teaches an array of Faraday cups supported in an insulating substrate. Likewise, the Hayafuji reference teaches a Faraday cup supported in an insulating substrate. The cited references fail to teach or suggest the claimed invention: an array of Faraday cups in which each cup is electrically and capacitively decoupled from all others by use of a "partially conductive housing in which the plurality of cups is supported, the conductive housing being electrically connected to a reference potential."

Because the cited references, either alone or in combination, fail to teach, suggest, provide any motivation to make, or otherwise render obvious the claimed invention, the claimed invention is nonobvious and patentable over the cited references. Withdrawal of this ground for rejection is respectfully requested.

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Conclusion

In view of the above amendments and foregoing remarks, applicants believe that Claims 59-88 are in condition for allowance. If any issues remain that may be expeditiously addressed in a telephone interview, the Examiner is encouraged to telephone applicants' attorney at 206-695-1755.

Respectfully submitted,

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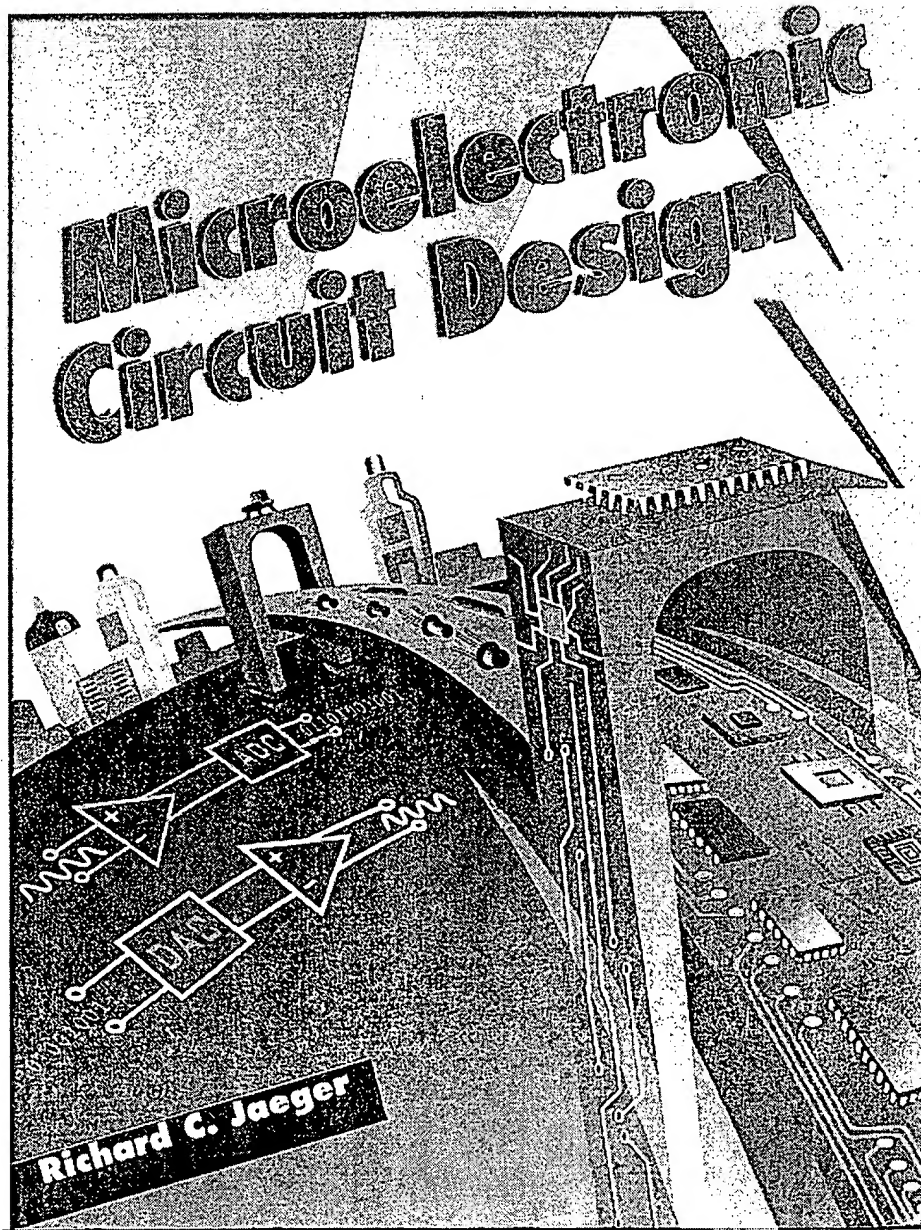
Date: September 3, 2004

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The evolution of solid-state materials and the subsequent development of the technology for integrated circuit fabrication have revolutionized electronics. Using silicon as well as other crystalline semiconductor materials, we can now fabricate integrated circuits (ICs) that have hundreds of millions of electronic components on a single 2 cm × 2 cm die. Most of us have some familiarity with the very high-speed microprocessor and memory components that form the building blocks for personal computers and workstations. As this edition is being written, technology for the 1-gigabit (Gb) memory chip is being developed in a number of research laboratories around the world. The memory array alone on this chip will contain more than 10^9 transistors and 10^9 capacitors—more than 2 billion electronic components on a single die!

Our ability to build such phenomenal electronic system components is based on a detailed understanding of solid-state physics as well as on development of fabrication processes necessary to turn the theory into a manufacturable reality. Integrated circuit manufacturing is an excellent example of a process requiring a broad understanding of many disciplines. IC fabrication requires knowledge of physics, chemistry, electrical engineering, mechanical engineering, materials engineering, and metallurgy, to mention just a few disciplines. The breadth of understanding required is a challenge, but it makes the field of solid-state electronics an extremely exciting and vibrant area of specialization.

The material in this chapter provides the background necessary for understanding the behavior of the solid-state devices presented in subsequent chapters. We begin our study of solid-state electronics by exploring the characteristics of crystalline materials, with an emphasis on silicon, the most commercially important semiconductor. We look at electrical conductivity and resistivity and discuss the mechanisms of electronic conduction. The technique of impurity doping is discussed, along with its use in controlling conductivity and resistivity type.

2.1 SOLID-STATE ELECTRONIC MATERIALS

Electrical Classification of Solid Materials

Materials	Resistivity ($\Omega \cdot cm$)
Insulators	$10^5 < \rho$
Semi-conductors	$10^{-3} < \rho$ $< 10^5$
Conductors	$\rho < 10^{-3}$

Electronic materials generally can be divided into three categories: insulators, conductors, and semiconductors. The primary parameter used to distinguish among these materials is the resistivity ρ, with units of $\Omega \cdot cm$. As indicated in Table 2.1, insulators have resistivities greater than $10^5 \ \Omega \cdot cm$, whereas conductors have resistivities below $10^{-3} \ \Omega \cdot cm$. For example, diamond, one of the highest quality insulators, has a very large resistivity, $10^{16} \ \Omega \cdot cm$. On the other hand, pure copper, a good conductor, has a resistivity of only $3 \times 10^{-6} \ \Omega \cdot cm$. Semiconductors occupy the full range of resistivities between the insulator and conductor boundaries; moreover, the resistivity can be controlled by adding various impurity atoms to the semiconductor crystal.

Elemental semiconductors are formed from a single type of atom (column IV of the periodic table of elements; see Table 2.2), whereas compound semiconductors can be formed from combinations of elements from columns III and V or columns II and VI. These later materials are often referred to as III–V (3–5) or II–VI (2–6) compound semiconductors. Table 2.3 presents some of the most useful possibilities. There are also ternary materials such as mercury cadmium telluride, gallium aluminum arsenide, gallium indium arsenide, and gallium indium phosphide.

Historically, germanium was one of the first semiconductors to be used. However, it was rapidly supplanted by silicon, which today is the most important semiconductor material. Silicon has a wider bandgap energy,[1] allowing it to be used in higher-temperature applications than germanium, and oxidation forms a stable insulating oxide on silicon,

---

[1] The meaning of bandgap energy is discussed in detail in Secs. 2.3 and 2.8.

Table 2.2

Portion of the Periodic Table, Including the Most Important Semiconductor Elements (shaded)

IIIA	IVA	VA	VIA
5 10.811 **B** Boron	6 12.01115 **C** Carbon	7 14.0067 **N** Nitrogen	8 15.9994 **O** Oxygen
13 26.9815 **Al** Aluminum	14 28.086 **Si** Silicon	15 30.9738 **P** Phosphorus	16 32.064 **S** Sulfur
30 65.37 **Zn** Zinc	31 69.72 **Ga** Gallium	32 72.59 **Ge** Germanium	33 74.922 **As** Arsenic	34 78.96 **Se** Selenium
48 112.40 **Cd** Cadmium	49 114.82 **In** Indium	50 118.69 **Sn** Tin	51 121.75 **Sb** Antimony	52 127.60 **Te** Tellurium
80 200.59 **Hg** Mercury	81 204.37 **Ti** Thallium	82 207.19 **Pb** Lead	83 208.980 **Bi** Bismuth	84 (210) **Po** Polonium

(IIB column header at left of Zn/Cd/Hg group)

Table 2.3

Semiconductor Materials

Semiconductor	Bandgap Energy E_G (eV)
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.00
Cadmium selenide	1.70

giving silicon significant processing advantages over germanium during fabrication of ICs. In addition to silicon, gallium arsenide and indium phosphide are commonly encountered today, although germanium is still used in some limited applications. The compound semiconductor materials gallium arsenide (GaAs) and indium phosphide (InP) are the most important material for optoelectronic applications, including light-emitting diodes (LEDs), lasers, and photo detectors.

Many research laboratories are now exploring the formation of diamond, boron nitride, silicon carbide, and silicon germanium materials. Diamond and boron nitride are excellent insulators at room temperature, but they, as well as silicon carbide, can be used as semiconductors at much higher temperatures (600°C). Adding a small percentage (<10 percent) of germanium to silicon has been shown recently to offer improved device performance in a process compatible with normal silicon processing.

EXERCISE: What are the chemical symbols for antimony, arsenic, aluminum, boron, gallium, germanium, indium, phosphorus, and silicon?

ANSWERS: Sb, As, Al, B, Ga, Ge, In, P, Si

2.2 DRIFT CURRENTS IN SEMICONDUCTORS

Electrical resistivity ρ and its reciprocal, conductivity σ, characterize current flow in a material when an electric field is applied. Charged particles move or *drift* in response to the electric field, and the resulting current is called *drift current*. The drift current density j is defined as

$$j = Qv \qquad (C/cm^3)(cm/s) = A/cm^2 \qquad (2.1)$$

where Q = charge density

v = velocity of charge in electric field

In order to find the charge density, we explore the structure of silicon using both the covalent bond model and (later) the energy band model for semiconductors. We relate the velocity of the charge carriers to the applied electric field in Sec. 2.4.

2.3 COVALENT BOND MODEL

Atoms can bond together in amorphous, polycrystalline, or single-crystal forms. Amorphous materials have a totally disordered structure, whereas polycrystalline material consists of a large number of small crystallites. Most of the highly useful properties of semiconductors, however, occur in high-purity, single-crystal material. Silicon—column IV in the periodic table—has four electrons in the outer shell. Single-crystal material is formed by the covalent bonding of each silicon atom with its four nearest neighbors in a highly regular three-dimensional array of atoms, as shown in Fig. 2.1. Much of the behavior we discuss can be visualized using the simplified two-dimensional covalent bond model of Fig. 2.2.

At temperatures approaching absolute zero, all the electrons reside in the covalent bonds shared between the atoms in the array, with no electrons free for conduction. The outer shells of the silicon atoms are full, and the material behaves as an insulator. As the temperature increases, thermal energy is added to the crystal and some bonds break, freeing a small number of electrons for conduction, as in Fig. 2.3. The density of these free electrons is equal to the intrinsic carrier density n_i (cm^{-3}), which is determined by material properties and temperature:

INTRINSIC CARRIER DENSITY

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad \text{cm}^{-6} \tag{2.2}$$

where E_G = semiconductor bandgap energy in eV (electron volts)

k = Boltzmann's constant, 8.62×10^{-5} eV/K

T = absolute temperature, K

B = material-dependent parameter, 1.08×10^{31} K$^{-3} \cdot$ cm^{-6} for Si

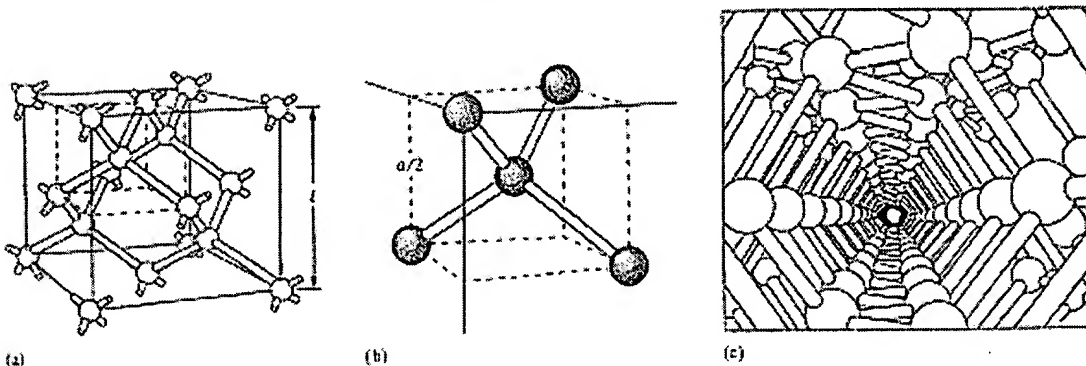(a)   (b)   (c)

Figure 2.1 Silicon crystal lattice structure. (a) Diamond lattice unit cell. The cube side length $l = 0.543$ nm. (b) Enlarged top corner of the diamond lattice, showing the four nearest neighbors bonding within the structure. (c) View along a crystallographic axis. [(a) and (b) adapted from *Electrons and Holes in Semiconductors* by William Shockley. © 1950 by Litton Educational Publishing. (c) adapted from *The Architecture of Molecules* by Linus Pauling and Roger Hayward, copyright © 1964 by W. H. Freeman and Company, used with permission; and *Semiconductor Devices: Physics and Technology* by S. M. Sze, copyright © 1985 by Bell Telephone Laboratories, by permission of John Wiley & Sons, Inc.]
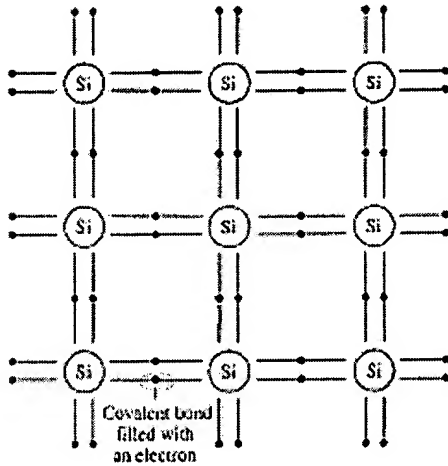
Figure 2.2 Two-dimensional silicon lattice with shared covalent bonds. At temperatures approaching 0 K, all bonds are filled, and the outer shells of the silicon atoms are completely full.
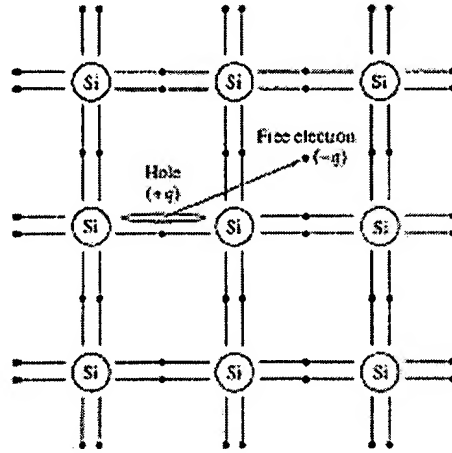
Figure 2.3 An electron–hole pair is generated whenever a covalent bond is broken.

Bandgap energy E_G is the minimum energy needed to break a covalent bond in the semiconductor crystal, thus freeing electrons for conduction. Table 2.3 lists values of the bandgap energy for various semiconductors.

The *density of conduction (or free) electrons* is represented by the symbol n (electrons/cm³), and for intrinsic material $n = n_i$. The term *intrinsic* refers to the generic properties of pure material. Although n_i is an intrinsic property of each semiconductor, it is extremely temperature-dependent for all materials. Figure 2.4 has examples of the strong variation of intrinsic carrier density with temperature for germanium, silicon, and gallium arsenide.

EXAMPLE 2.1: As an example, let us calculate the value of n_i in silicon at room temperature (300 K):

$$n_i^2 = 1.08 \times 10^{31} (\mathrm{K}^{-3} \cdot \mathrm{cm}^{-6})(300\ \mathrm{K})^3 \exp\left(\frac{-1.12}{(8.62 \times 10^{-5}\ \mathrm{eV/K})(300\ \mathrm{K})}\right)$$

$$n_i^2 = 4.52 \times 10^{19}/\mathrm{cm}^6 \qquad \text{or} \qquad n_i = 6.73 \times 10^9/\mathrm{cm}^3$$

For simplicity, in subsequent calculations we use $n_i = 10^{10}/\mathrm{cm}^3$ as the room temperature value of n_i for silicon.   ◈

The density of silicon atoms in the crystal lattice is approximately $5 \times 10^{22}/\mathrm{cm}^3$. We see from Example 2.1 that only one bond in approximately 10^{13} is broken at room temperature.

A second charge carrier is actually formed when the covalent bond in Fig. 2.3 is broken. As an electron, which has charge $-q$ equal to -1.602×10^{-19} C, moves away from the covalent bond, it leaves behind a vacancy in the bond structure in the vicinity of its parent silicon atom. The vacancy is left with an effective charge of $+q$. An electron from an adjacent bond can fill this vacancy, creating a new vacancy in another position. This process allows the vacancy to move through the crystal. The moving vacancy behaves just
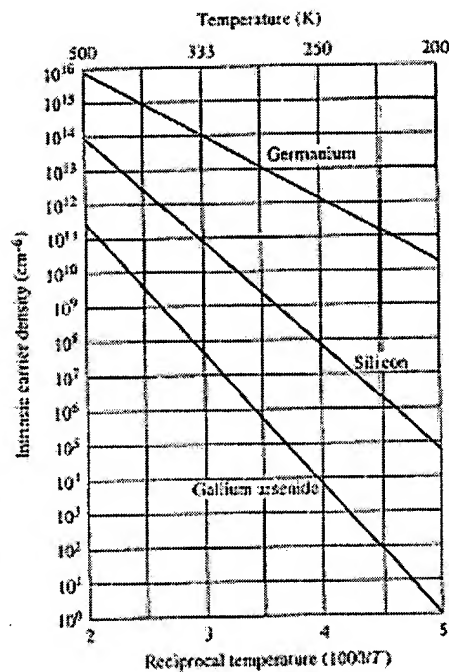
Figure 2.4 Intrinsic carrier density versus temperature from Eq. (2.2), using $B = 1.08 \times 10^{31}\ K^{-3} \cdot cm^{-6}$ for Ge, $B = 2.31 \times 10^{30}\ K^{-3} \cdot cm^{-6}$ for Si, and $B = 1.27 \times 10^{29}\ K^{-3} \cdot cm^{-6}$ for GaAs.

as a particle with charge $+q$ and is called a hole. Hole density is represented by the symbol p (holes/cm^3).

As described above, two charged particles are created for each bond that is broken: one electron and one hole. For intrinsic silicon,

$$n = n_i = p \tag{2.3}$$

and the product of the electron and hole concentrations is

$$pn = n_i^2 \tag{2.4}$$

The pn product is given by Eq. (2.4) whenever a semiconductor is in thermal equilibrium. (This very important result is used later.) In thermal equilibrium, material properties are dependent only on the temperature T, with no other form of stimulus applied. Equation (2.4) does not apply to semiconductors operating in the presence of an external stimulus such as an applied voltage or current or an optical excitation.

> EXERCISE: Calculate the intrinsic carrier density in silicon at 50 K and 325 K. On the average, what is the length of one side of the cube of silicon that is needed to find one electron and one hole at $T = 50$ K?
>
> ANSWERS: 4.34×10^{-39}/cm^3; 4.01×10^{10}/cm^3; 6.13×10^{10} m

2.4 MOBILITY

As discussed earlier, charged particles move in response to an applied electric field. This movement is termed drift, and the resulting current flow is known as drift current. Positive

charges drift in the same direction as the electric field, whereas negative charges drift in a direction opposed to the electric field. Carrier drift velocity v (cm/s) is proportional to the electric field E (V/cm); the constant of proportionality is called the mobility μ:

$$v_n = -\mu_n E \qquad \text{and} \qquad v_p = \mu_p E \tag{2.5}$$

where v_n = velocity of electrons (cm/s)
v_p = velocity of holes (cm/s)
μ_n = electron mobility, 1350 cm²/V · s in intrinsic Si
μ_p = hole mobility, 500 cm²/V · s in intrinsic Si

Conceptually, holes are localized to move through the covalent bond structure, but electrons are free to move about the crystal. Thus, one might expect hole mobility to be less than electron mobility, as appears in the definitions in Eq. (2.5). Note that the relationship in Eq. (2.5) breaks down at high fields in all semiconductors because the velocity of carriers reaches a limit called the **saturated drift velocity** v_{sat}. In silicon, v_{sat} is approximately 10^7 cm/s for electric fields exceeding 3×10^4 V/cm.

> **EXERCISE:** Calculate the velocity of a hole in an electric field of 10 V/cm. What is the electron velocity in an electric field of 1000 V/cm? The voltage across a resistor is 1 V, and the length of the resistor is 2 μm. What is the electric field in the resistor?
>
> **ANSWERS:** 5.00×10^3 cm/s; 1.35×10^6 cm/s; 5.00×10^3 V/cm.

2.5 RESISTIVITY OF INTRINSIC SILICON

We are now in a position to calculate the electron and hole drift current densities j_n^{drift} and j_p^{drift}. For simplicity, we assume a one-dimensional current and avoid the vector notation of Eq. (2.1):

$$j_n^{drift} = Q_n v_n = (-qn)(-\mu_n E) = qn\mu_n E \qquad \text{A/cm}^2$$
$$j_p^{drift} = Q_p v_p = (+qp)(+\mu_p E) = qp\mu_p E \qquad \text{A/cm}^2 \tag{2.6}$$

in which $Q_n = (-qn)$ and $Q_p = (+qp)$ represent the charge densities (C/cm³) of electrons and holes, respectively. The total drift current density is then given by

$$j_T^{drift} = j_n + j_p = q(n\mu_n + p\mu_p)E = \sigma E \tag{2.7}$$

This equation defines σ, the **electrical conductivity**:

$$\sigma = q(n\mu_n + p\mu_p) \qquad (\Omega \cdot \text{cm})^{-1} \tag{2.8}$$

For intrinsic silicon, the charge density of electrons is given by $Q_n = -qn_i$, whereas the charge density for holes is $Q_p = +qn_i$. The values of the mobilities in intrinsic silicon were given in Eq. (2.5), and

$$\sigma = (1.60 \times 10^{-19})[(10^{10})(1350) + (10^{10})(500)] \qquad (\text{C})(\text{cm}^{-3})(\text{cm}^2/\text{V} \cdot \text{s})$$
$$= 2.96 \times 10^{-6} \, (\Omega \cdot \text{cm})^{-1}$$

The resistivity ρ is equal to the reciprocal of the conductivity, so for intrinsic silicon

$$\rho = \frac{1}{\sigma} = 3.38 \times 10^5 \, \Omega \cdot \text{cm} \tag{2.9}$$

From Table 2.1, we see that intrinsic silicon can be characterized as an insulator, albeit near the low end of the insulator resistivity range.